The three phased analysis and preliminary design approach developed for the HSSD was subsequently used, with refinements, on the other two districts comprising Skokie. Preliminary engineering was completed for both the MSSD and the ELSSD in 1987 (Donohue, May 1987a; Donohue, May 1987b). Thus, the substantial investment in developing the computer modeling-based analysis and preliminary design methodology for the HSSD yielded returns, not only on that district but also on the other two. As described in the next section, some of the modeling approach developed for Skokie was used in Wilmette.

Analysis and Preliminary Design in Wilmette

The USEPA Stormwater Management Model (SWMM) (Huber and Dickinson, 1992) was modified for analysis and preliminary design of the Wilmette street storage system (Loucks and Morgan, 1995). The modeling approach consisted of:

- Hydrologic simulation using the SWMM RUNOFF module.
- Street storage simulation using the SWMM EXTRAN module.
- Sewer system simulation using the SWMM EXTRAN module.

The EXTRAN model of the Wilmette street storage system is a surface network of storage junctions and berm overflows connected to a subsurface combined and relief sewer system.

Modification of the Stormwater Management Model

Street storage simulator required three innovations, including two modifications. As explained by Loucks and Morgan (1995):

> *Three innovations were required in the development of the street storage model. First, the EXTRAN code was modified to accept input of stage-storage relations for storage junctions and to generate descriptive storage junction output summaries of storage junction levels and outflow. Second, it was determined that the standard EXTRAN orifice formulation did not adequately represent field conditions for flow through a catch basin restrictor. An alternate to the equivalent pipe formulation was developed for use in the EXTRAN model. Third, the EXTRAN weir code was used to model flow overtopping of the berms into adjacent street storage sites.*

Each of the three SWMM innovations are now explained. This somewhat detailed explanation is provided primarily because SWMM is widely used in modeling urban wet weather conditions. Accordingly, communities contemplating a street storage system may also be thinking of using SWMM.

In the standard use of EXTRAN, storage junction data are input in the form of a depth and surface area relationships. Such a relationship is difficult to develop directly from street storage sites. This problem was resolved as follows (Loucks and Morgan, 1995):

> *Available street storage volumes are from street cross-sections using the end area method. Software is available to compute street storage at depth intervals of 0.1 feet. The EXTRAN code was modified to accept stage verus storage volume input and to print an enhanced summary of storage junction results. The summary provides the maximum depth, storage and discharge for each storage site and identifies whether an overflow from the junction occurred.*

The software referred to in the preceding quote is SASAM, the previously described computer model used in the Skokie modeling. It was used to develop stage-storage relationships in the Wilmette project.

EXTRAN uses an equivalent pipe to represent an orifice. This representation differed greatly from the manner in which flow regulators were to be installed in Wilmette catch basins. For example, inherent in EXTRAN is the assumption that the water depth in the upstream junction exceeds the orifice diameter and that upstream and downstream junction elevations are about the same. This differs markedly from the expected Wilmette flow regulator installations, as shown in Figure 3-19, where the flow regulators are 1.5 to 4.5 feet below street grade and the receiving combined sewer is three to nine feet below the flow regulators. EXTRAN provided no way to position an orifice well below the storage junction invert. As explained by Loucks and Morgan (1995), the complication was resolved as follows:

> *Laboratory tests by Spring (1983) demonstrated that a PVC tee-restrictor in a catch basin behaves as a classical orifice for a wide range of heads. The flow for a particular orifice area and head is given by formula $Q=C_d a(2gh)^{1/2}$, where g is acceleration due to gravity and C_d is a discharge coefficient found to be 0.60 to 0.65. In the context of the EXTRAN model, this formula is much better suited to the EXTRAN weir code rather than an equivalent pipe representation. The EXTRAN weir code was modified to accept a new type of weir representing a catch basin restrictor. Data inputs are the orifice diameter, the depth of the orifice below the ground, and the discharge coefficient. This approach is superior as long as there is no downstream submergence. Even then it is still more accurate than the equivalent pipe, but not as stable computationally.*

Berm overflow and flow exchange between adjacent street storage areas are important phenomena in the street storage system. All stormwater flow and volume must be accounted for. As explained by Loucks and Morgan (1995):

> *Berm overflow is employed to fully utilize available storage and to convey stormwater to relief sewer locations from individual ponding areas, which may not have sufficient storage volume. Simulation of berm overflow has been implemented in the EXTRAN model using the standard transverse weir input.*

Application of the Model

The previously described model was used for analysis, preliminary design, final design, and post-construction verification. More specifically (Loucks and Morgan, 1995):

> *In the feasibility analysis, storage sites were grouped together using a single storage junction to represent ten or more ponding areas. During design and construction, the planning level models were refined to support and verify the design of street storage location, relief sewer configurations, relief sewer connections to existing combined sewers, and restrictor sizes. These models stretched the traditional data limits of EXTRAN. Current models representing the two completed phases feature over 250 pipes and 350 junctions including more than 100 storage junctions.*

The model was calibrated against precipitation and flow data for July 13 and July 30, 1992 storm events, each of which had recurrence intervals of about three months. Analyses of sensitivity of the system to design storm duration revealed that the six hour event "...produced the greatest amount of system overflow and the most prolonged time of widespread sewer surcharge." System analysis indicated that one-year frequency and larger storm events surcharge the CSS and cause basement and street flooding (Rust, November 1993, p. 4). This finding was consistent with Wilmette's historic basement and street flooding problems.

Results

The engineer recommended implementing the street storage system in Wilmette as a result of the previously described computer modeling based analysis and design process. Wilmette accepted the recommendation and implementation of the street storage approach will eventually encompass the entire 2.0 square mile CSS.

Review Flow Regulator Availability and Performance

Essentiality of Flow Regulators

Flow regulators, as explained earlier in this chapter, are an integral part of the street storage system. They must be properly sized to achieve the desired stage-discharge relationship at any given storage location.

Equally important is selection of the type of flow regulator for a particular application. Reason: relative to berms, subsurface tanks, relief sewers and other components, flow regulators are most prone to failure. The most common failure mechanism is partial or total plugging by debris carried in stormwater runoff. Plugging can, in turn, lead to excessive upstream storage and stage and, after a rainfall event, prevent the gravity drainage of stored stormwater. Therefore, the type of flow regulator selected must fit the environment within which it is installed.

Skokie Flow Regulator Study

A flow regulator testing program was carried out in the early stages of the Skokie street storage project. It had been recommended in the preliminary engineering study for the HSSD (Donohue, 1982a, p. 115). At that time, in the early 1980's, little was known about flow regulators. Flow regulators were viewed as likely pivotal components of the evolving Skokie street storage program, and, therefore, a special flow regulator study was warranted.

Presented here is a synopsis of the testing program based largely on Donohue (March 1984a). The first purpose of the synopsis is to sensitize potential uses of flow regulators to flow regulator features so that informed decisions can be made. The second purpose of this synopsis is to provide information about specific flow regulators.

Purpose

The overall purpose of the flow regulator study was an equitable and objective evaluation of flow regulators under field conditions likely to be encountered in a system-wide application of regulators in Skokie. Sometimes laudatory and occasionally conflicting claims of equipment manufacturers and suppliers pointed to the need for a comparative field test. Based on a literature search and personal contacts, such a test had apparently never been carried out.

More specifically, the purpose of the flow regulator study was to: determine the initial cost of commercially available flow regulators and devices specially fabricated by the Village and others: evaluate flow regulator installation, removal and adjustment requirements: and observe and evaluate the hydraulic and other performance characteristics of flow regulators under a variety of field conditions.

Literature Search and Interviews

A literature survey and personal interviews identified the following five types of flow regulators potentially applicable to the HSSD:

1. The commercially available Hydro-Brake unit as illustrated in Figure 3-28. Flow enters the unit perpendicular to the outlet pipe, is turned through 90 degrees, and is discharged. The resulting turbulent flow pattern causes a

much higher energy loss than would occur through an orifice of similar diameter. Therefore, for a given head, the discharge through a Hydro-Brake was half or less than half that which would occur through an orifice having a cross-sectional area equal to the smallest free opening of the Hydro-Brake. That is, although the Hydro-Brake and the orifice would have similar ability to pass debris, the Hydro-Brake would reduce flows by one-half or more.

As noted by Pisano (1989), the Hydro-Brake is an example of a vortex flow throttling device. Vortex regulators were first developed in Denmark in the mid 1970's. They were used in Denmark and Sweden to mitigate basement flooding within CSSs.

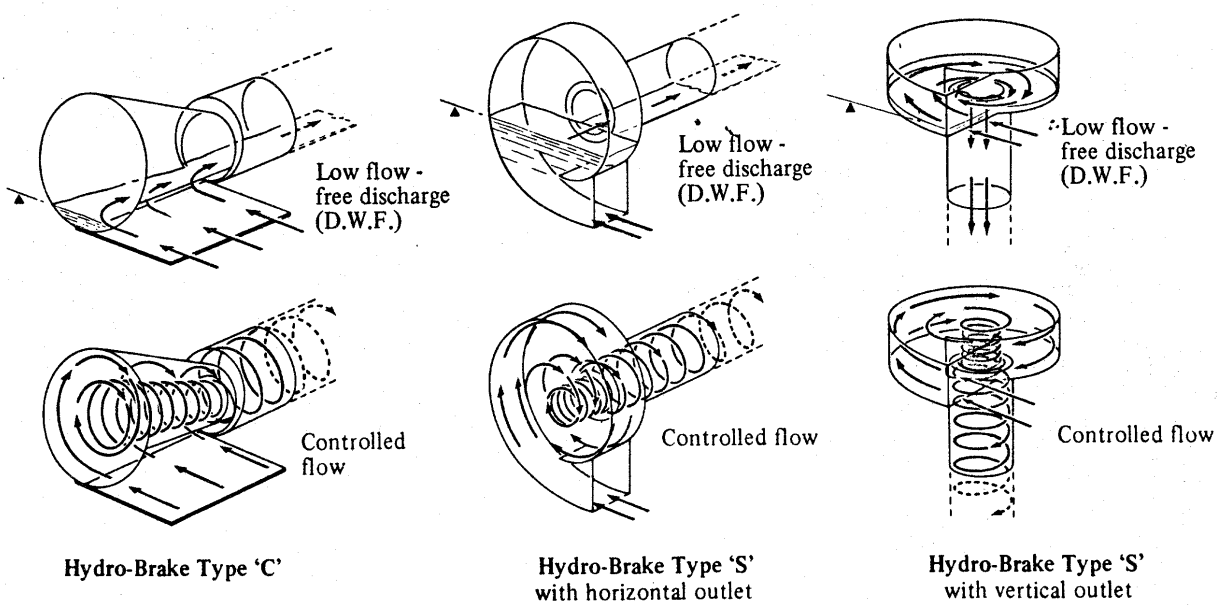

Figure 3-28. Examples of Hydro-Brake flow regulators, available in the early 1980's, illustrating the basic operation of vortex type regulators (Source: Hydro Group, 1982).

2. The commercially available Scepter units. A photograph of one is shown in Figure 3-29. The orifice is diamond shaped with a rectangular keyway at the bottom. The principal purpose of the keyway is to keep buoyant debris below the bottom of the diamond during dry periods. At the onset of a runoff event, the device is expected to function such that buoyant debris jammed against the keyway will rise, encounter the wider diamond portion of the orifice, and immediately flow through the regulator.

3. Specially fabricated solid cover with orifices. Figure 3-30 is a photograph of one of these devices. For a given head, a few small orifices reduce the flow significantly compared to the flow through a standard inlet grate with its many larger openings.

4. Horizontal orifice plate beneath the inlet grate as shown in the photographs in Figure 3-31. The single, small orifice helps to trap leaves, twigs and other debris carried by the stormwater before the material reaches the underlying orifice.

5. Hanging trap flow regulator, as illustrated in Figure 3-32. This device, which can be assembled from inexpensive, standard PVC units, features an orifice that is always submerged.

Design of the Field Study

Portions of four streets, covering approximately ten lineal blocks on the west side of the HSSD, were selected for the field phase of the flow regulator study. Factors considered in selecting the test areas included: a variety of topographic features such as streets with uniform and non-uniform longitudinal slopes; a range in type of street cross-sections and street widths; an aerial density of inlets and catch basins similar to that of the entire HSSD; a mix of residential and commercial streets; and the presence of trees.

Equipment Acquisition and Installation

A total of 29 flow regulators were installed in the study area during the period of January through April 1983. The Hydro-Brake and Scepter units were installed in both catch basins and inlets. The hanging trap unit was applicable only to catch basins. The orifice in the inlet grate and the horizontal orifice plate beneath the grate were suited only to inlet installations.

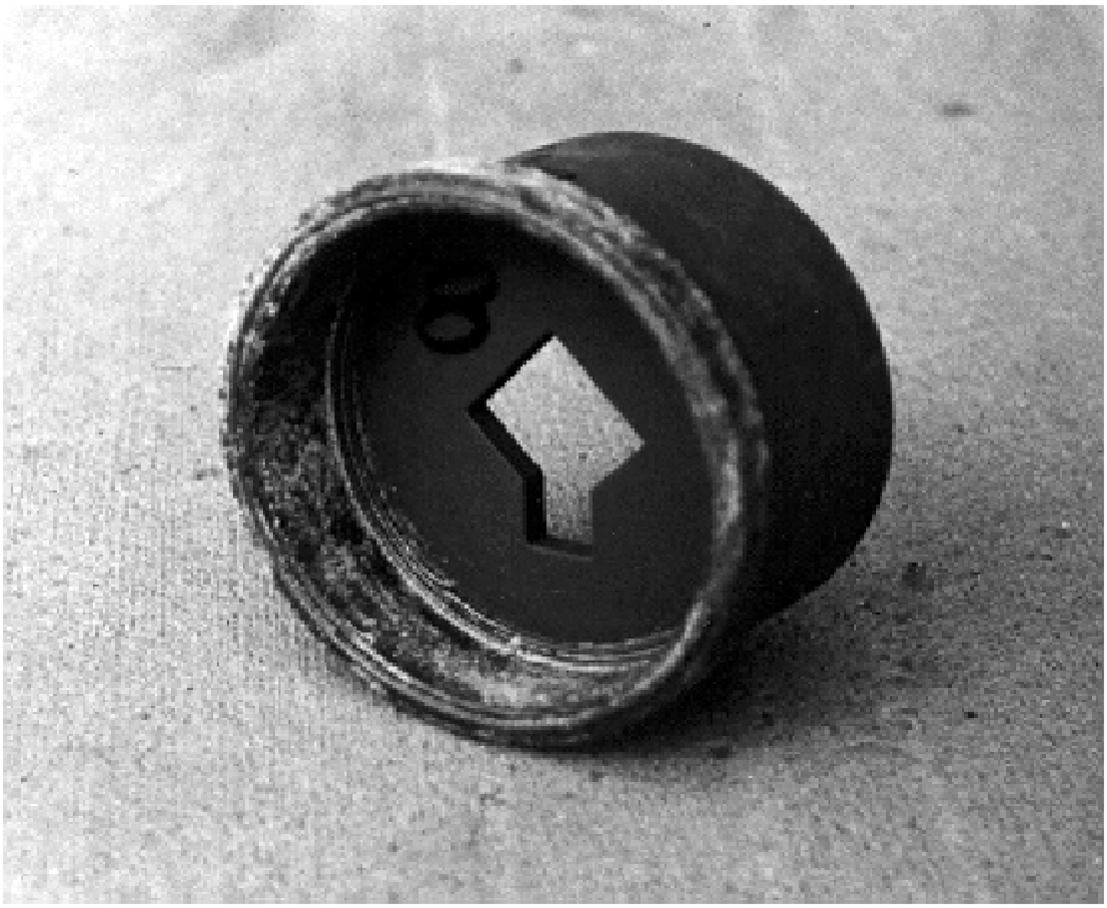

Figure 3-29. Photograph of Scepter flow regulator.

Figure 3-30. Photograph of solid cover with orifices.

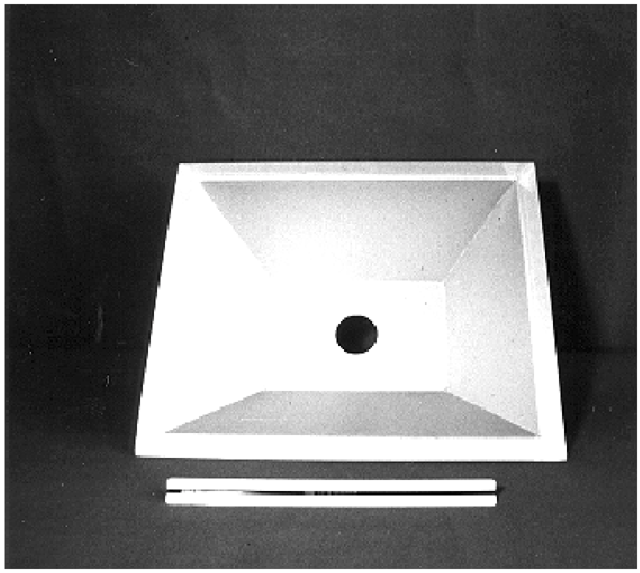

Figure 3-31. Photographs of horizontal orifice plate flow regulator before and after installation.

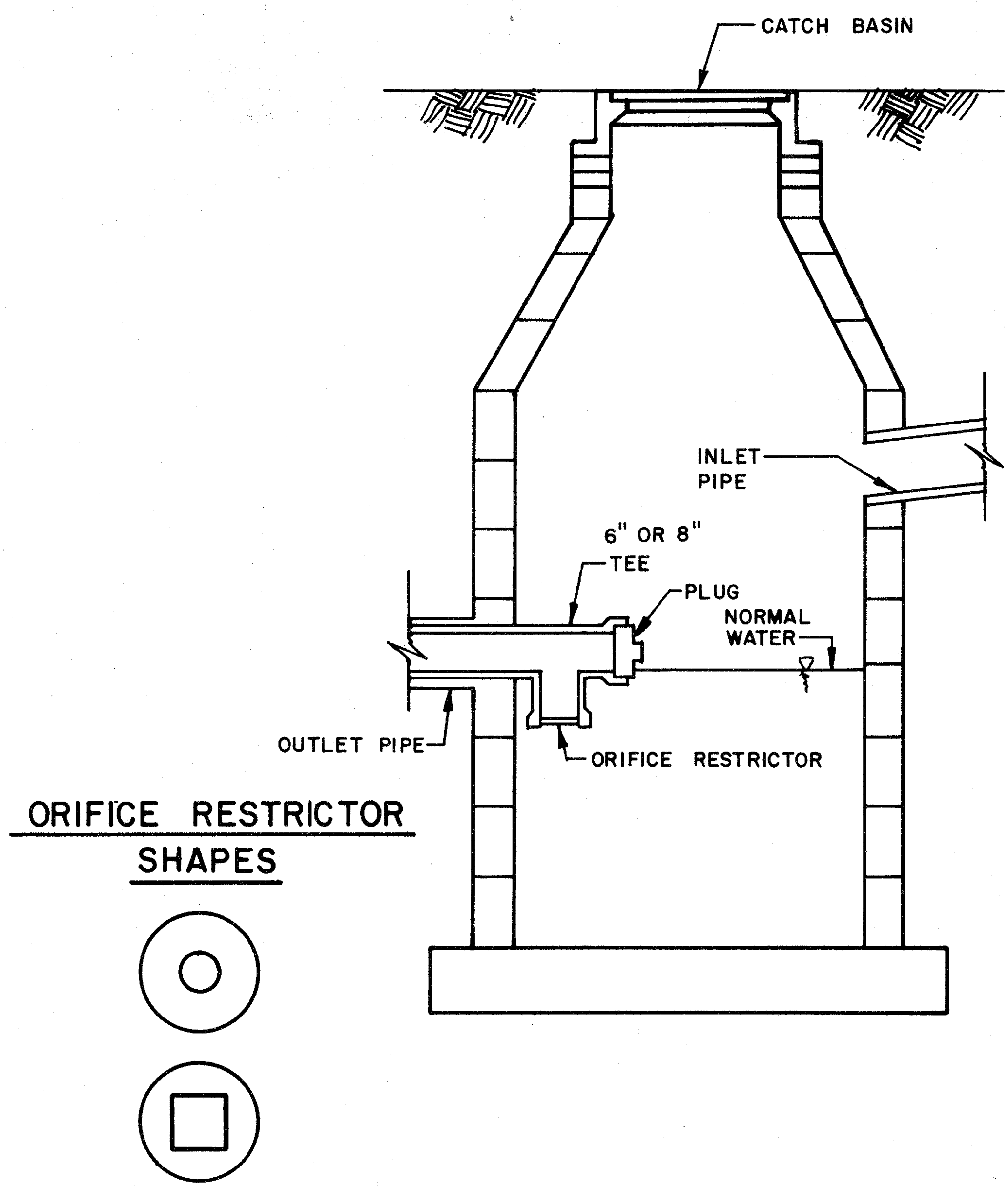

Figure 3-32. Hanging trap flow regulator (Source: Donohue, 1982a).

Observation Procedures

The system of 29 flow regulators was observed by Skokie and Donohue personnel during or immediately after a total of 15 rainfall-runoff events between March 18 and September 20, 1983. In addition, regulator performance was observed during intentional flooding tests conducted on October 18 and November 16, 1983. A photograph of the intentional street flooding is shown in Figure 3-33. The field observations of flow regulators focused on operation and maintenance factors such as the tendency of the regulators to plug with leaves and other debris and the ease of removing material from plugged regulators.

Rainfall

The average intensity of 60 percent of the rainfall events occurring during the six month field tests exceeded 0.1 inches per hour which approximately corresponds to a unit runoff rate of about 0.1 cfs per acre, the rate above which flow regulators had to function as part of the HSSD street storage system to prevent damaging surcharging. Therefore, the majority of rainfall events, and all intentional flooding tests, simulated operational conditions.

Resistance to Plugging

From a plugging perspective, flow regulators were much more resistant to plugging when placed in catch basins than inlets—the latter installations were 20 times more likely to plug than the former. There was no significant difference in the operation characteristics of Hydro-Brakes, Scepter units, and hanging traps placed in catch basins—they all performed very well.

Although there were significant differences in the anti-plugging performance of inlet installations of Hydro-Brakes, Scepter units, grate modifications and horizontal orifice plates, the difference was of little practical significance because the incidence of plugging was too high. That is, even a relatively low plugging frequency of inlet installation is unacceptable for the street storage system. Leaves appeared to be the principal cause of plugging of flow regulators. This dominance probably reflects the large supply of leaves relative to other materials.

Costs

The cost of purchasing flow regulators varied widely. Cost ranges per unit in 1983 for units appropriate to Skokie inlet or catch basin installations were:

Figure 3-33. Streets were intentionally flooded to test the performance of flow regulators.

- Hydro-Brake: $300 - $800
- Scepter: $100 - $130
- Solid cover with orifice: $10 - $50
- Horizontal orifice plate beneath inlet grate: $50 - $150
- Hanging trap: $25 - $50

Given the good and similar operating characteristics of Hydro-Brakes, Scepter units, and hanging traps, the hanging traps were clearly preferable because of their very low costs.

Maintenance

The ease with which debris can be removed from plugged flow regulators was difficult to quantify. The debris removal effort, listed in order of increasing difficulty, is approximately as follows: modified grate flow regulators; horizontal orifice plate positioned beneath the inlet grates; Hydro-Brake and Scepter flow regulators installed in inlets; and Hydro-Brakes, Scepter units, and hanging traps installed in catch basins.

Conclusions for Skokie

1. Flow regulators should be installed in catch basins, rather than inlets.

2. Hanging trap flow regulators should be used throughout the HSSD, except where the desired reduction and resulting orifice size is beyond the effective lower range of the hanging trap regulator, in which case Hydro-Brake flow regulators should be used.

3. A field-oriented flow regulator design process should be used to minimize costs.

4. The design and installation of flow regulators should be done in conjunction with other components of recommended street storage system including roadway berms, subsurface storage tanks, and relief sewers.

Complete Design of the Street Storage System

The goal of final design is to produce a set of plans and specifications to be used by contractors for bidding and by the selected contractors for construction. Additional hydrologic-hydraulic modeling is needed for tasks such as final sizing of flow regulators and refinement of berm locations and heights. However, the final design process is typical of that which might be done for an urban street. An example of the kind of detail that results is shown in Figure 3-34.

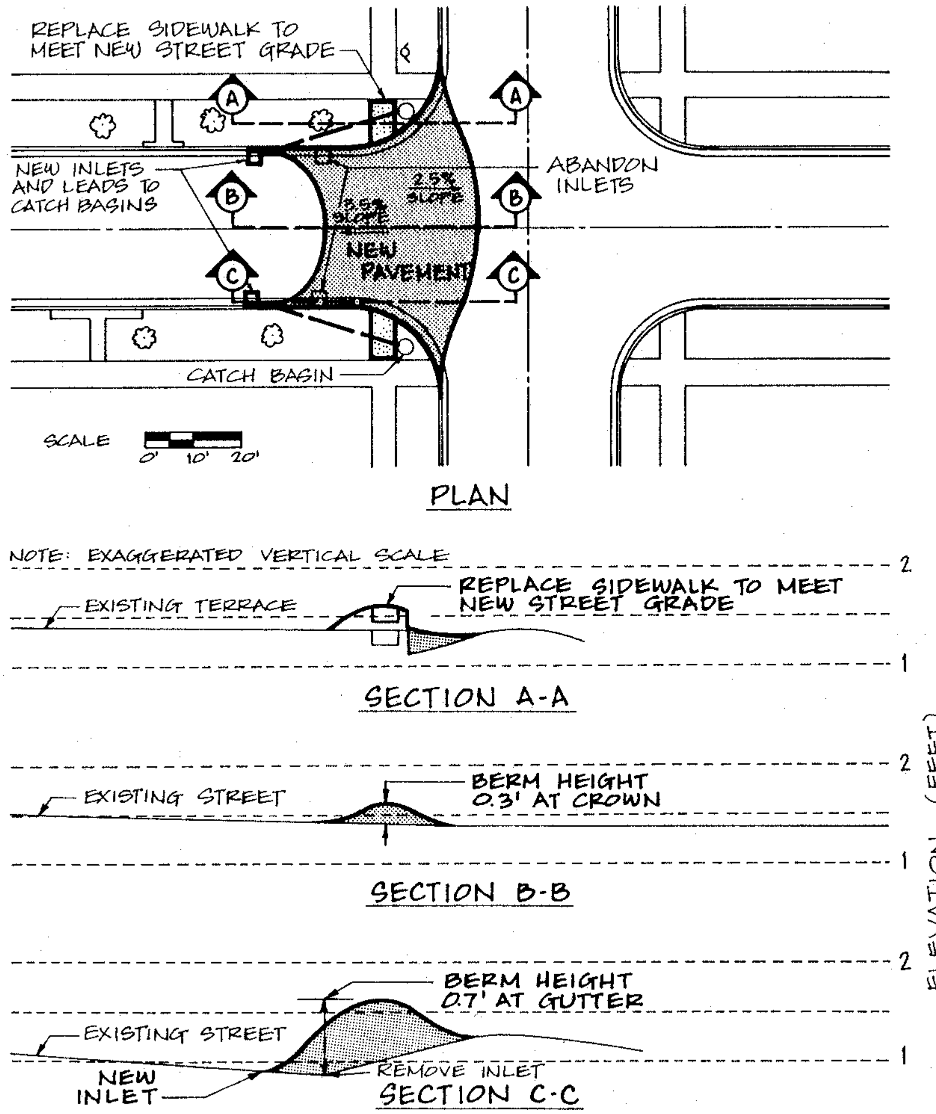

Figure 3-34. Typical street berm design in Skokie, IL (Source: Walesh, 1989, p. 401).

Construction

Both Skokie and Wilmette are using a phased approach to construction. (For a discussion of the advisability of phased implementation and suggested prioritization factors, refer to the earlier section of the chapter titled "Select an Initial Implementation Area Within the Combined Sewer System.") Each community's overall implementation schedule, with emphasis on construction, is summarized here.

Skokie Construction

Skokie implemented the physical aspects of its street storage system according to the following schedule:

- 1981: Initiate downspout disconnection
- 1983: Begin stakeholder involvement
- 1983: Test flow regulators in pilot areas
- 1983: Initiate base line monitoring
- 1983-1986: Construct HSSD
- 1988-1997: Construct MSSD
- 1989-1999: Construct ELSSD

Table 3-3 summarizes the components of the Skokie street storage system. Note the heavy reliance on berm-flow regulator installations, which suggest, in turn, widespread use of temporary, controlled street ponding.

The relative importance of street storage versus other storage is shown in Figure 3-35. Overall, street storage accounts for half of the total stormwater storage capacity in Skokie, the other half being subsurface storage and off-street surface storage. Incidentally, in Wilmette essentially all of the storage is street storage because there are no subsurface or off-street storage facilities.

The preceding observations about the dominance of street storage in Skokie and Wilmette reinforce the discussion near the beginning of this chapter about the significant storage and conveyance capacity of street, especially in a CSS. With carefully engineered retrofitting, that storage and conveyance can be the basis for cost-effective solutions to flooding and perhaps other wet weather problems in CSSs.

Table 3-3. Components of the Skokie street storage system (Source: Carr, 1999).

Component	Number	Length (Feet)
Flow Regulators	2,900	- - -
Berms	871	- - -
Off-Street Surface Storage	10	- - -
Subsurface Storage	83	- - -
Storm Sewer	- - -	64,000
Combined Sewer	- - -	29,000

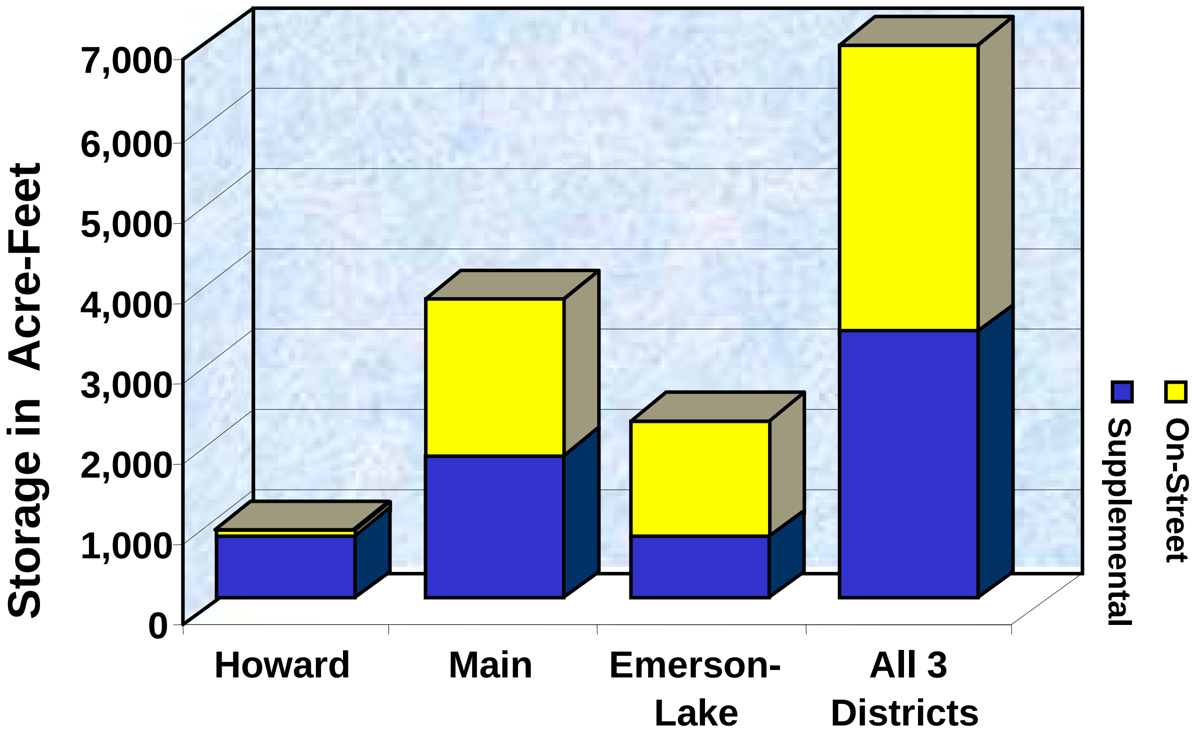

Figure 3-35. Street storage accounts for half of the total stormwater storage in Skokie (Source: Carr, 1999).

Wilmette Construction

A five-phased construction program is underway in Wilmette. Three phases are completed and two are planned. Two major considerations determined the priorities. The first was functional dependence. For example, downstream relief sewers were constructed before upstream relief sewers. The second of the two key prioritization factors was cost effectiveness. That is, higher priority was given to areas with the most severe problems. The five phases, with their actual construction costs (Phases 1, 2 and 3) and projected construction costs (Phases 4 and 5) are described below.

Phase 1: Greenleaf Avenue Relief Sewer

Included installation of approximately 6300 lineal feet of relief sewer (48" - 96") in Greenleaf Avenue, connection to the deep tunnel, emergency overflow to the North Shore Channel, and 165 berms and associated catch basins and flow regulators.

Cost: $10,358,000

Phase 2: Eastside Relief Sewer

Consisted of the continuation of relief sewers from Greenleaf Avenue, along 9th Street and Forest Avenue to 15th Street. This tunneled sewer project consisted of approximately 5600 lineal feet of 72", 54", and 48" diameter sewers. This phase also included the construction of 50 berms and related catch basins and flow regulators.

Cost: $4,586,000

Cumulative Cost: $14,944,000

Phase 3: Eastside Relief Sewer

Included both construction of relief sewer to the south from Greenleaf Avenue and a storm sewer system (including an outfall to the North Shore Channel) in the Maple/Dupee portion of the Village. This Phase included the construction of 37 berms and related catch basins and flow regulators.

Cost: $8,425,000

Cumulative Cost: $23,369,000

Phase 4: Eastside Lateral Relief Sewer

Will consist of the construction of relief sewers in 9th Street from Forest Avenue to Chestnut; Ashland Avenue from 9th Street to 8th Street; 8th Street from Ashland

Avenue to Chestnut Avenue; 12th Street from Forest Avenue to Ashland Avenue with one block stubs on Elmwood, Greenwood, and Ashland; 17th Street from Lake Avenue to Forest; and 17th Street from Forest Avenue to Elmwood Avenue. These sewers will range in size from 18" to 36" in diameter.

Cost: $4,500,000

Cumulative Cost: $27,869,000

Phase 5: Eastside Lateral Relief Sewer

Will consist of relief sewers in 6th Street from Greenleaf Avenue to Elmwood Avenue; Forest Avenue from 6th Street to Michigan Avenue; Elmwood Avenue from Sheridan Road to Michigan Avenue; and Washington Avenue from Prairie to Green Bay Road. A portion of the Phase 5 sewers will be constructed in Green Bay Road as part of the Green Bay Road resurfacing project. This phase will also include storm sewers at various locations across the Village. These sewers are proposed to pick up primarily surface drainage from low lying areas.

Cost: $7,300,000

Cumulative Cost: $35,169,000

In summary, as of early 1999, the constructed three phases of the street storage system in Wilmette's two square mile CSS consist of:

- 252 berms - catch basins - regulator installations. Over 98% of the intended 717,540 ft^3 (16.5 acre-feet) of street storage has already been achieved.
- Over 11,900 lineal feet of tunneled or conventionally constructed relief sewer.
- Incidental storm sewers.

The $23,369,000 total cost of the three completed phases consists of $18,946,000 or 81.1%, for relief sewers and $4,423,000 or 18.9%, for berms and associated catch basins and flow regulators.

Because the CSS is essentially one system, all phases must be completed to achieve the intended degree of flood control. The last two phases of the five phased program are not yet constructed.

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